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INVESTIGATION OF SELF-DISCHARGE CHARACTERISTICS OF  
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CA CHEMISTRY AND PHYSICS LAB S W DONLEY ET AL.

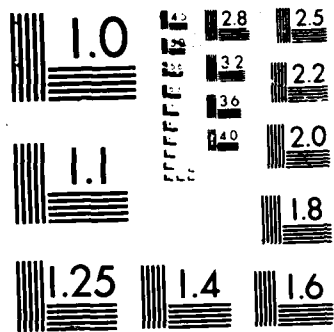
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Investigation of Self-Discharge  
Characteristics of Spacecraft  
Nickel-Cadmium Cells at  
Elevated Temperatures

S. W. DONLEY, J. H. MATSUMOTO, T. M. POSTON,  
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15 August 1987

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Los Angeles Air Force Station  
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Los Angeles, CA 90009-2960

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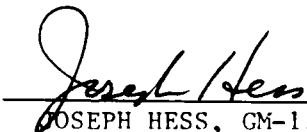
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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



THOMAS WETTERSTROEM, Lt, USAF  
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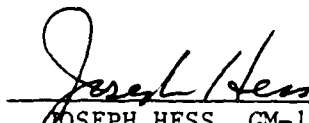
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## 1. INTRODUCTION

The objective of this report is to determine the heat generation rate in spacecraft nickel-cadmium (NiCd) cells during high temperature storage on open circuit. When NiCd batteries are open circuited in the charged state, chemical reaction(s) provide a means of self-discharge and heat generation. The rates of self-discharge and heat generation are relatively low at normal spacecraft operation temperatures (-5 to 30°C); however, the rates and possibly the complexity of the reactions increase with temperature. There are little data available concerning capacity losses via self-discharging in NiCd cells due to elevated temperature (above 40°C) exposure. Such data would be useful in determining the maximum allowable temperature from a safety standpoint in contingency scenarios such as mission aborts. At elevated temperatures, heating generated by battery self-discharge may drive the batteries into catastrophic failure with consequences for the integrity of the spacecraft and its contents. The testing described here was designed to determine the extent to which battery thermal stability is a valid concern, at initial temperatures of exposure (externally effected) between 44 and 118°C.

The heats generated by the open-circuited charged cells at 40°C and above were determined from calculations and measurements of cell specific heat and heat loss rate of the test apparatus, and by monitoring the cell temperature and cell-test apparatus temperature differentials during heat generation. Two different cells were used at each of four temperatures, and one at the highest temperature of 118°C. No cells were reused with the exception of those initially used at 44°C, where there was little heat generation.

## II. PROCEDURE/APPARATUS

The NiCd cells selected for testing are the type used in the AFP-888 program and are General Electric catalog number 42B035AB11, 35 Ah nominal capacity. It is expected that the results obtained with these cells will be readily extended to other NiCd spacecraft cells.

The cells were enclosed in an insulating container (Fibrothal®, Kanthal Furnace Products Company) prior to test. The cell test apparatus is shown in Fig. 1, which is not drawn to exact scale in order to show some of the details. The large faces of the cell were supported by 1/4 in. aluminum restraints which were held together by four screws (not shown in drawing). The cell and restraints were designed to slip into the aluminum liner along with the heater and aluminum shims to provide a snug fit. All sliding pieces were coated with silicone heat conducting compound. The liner was bonded to the Fibrothal container with a high thermal conductivity room temperature vulcanizing (RTV) compound. Empty spaces within the insulating container (top, bottom, and small side faces of cell) were filled with glass wool. Thermistors were mounted (see Fig. 1) at the top and bottom of the cell, on the outside of the cell restraint opposite the heater, on the inside of a small face of the liner, on two outside surfaces of the foam insulator, and at the bottom of the foam insulator. The insulated test assembly was operated inside an environmental chamber. The seven thermistors and the strain gauge measurements were monitored by a computer which also controlled the heater inside the foam insulator and the temperature of the environmental chamber (Fig. 2).

Calibrations of the thermistors, specific heat of the test apparatus, and thermal conduction through the test apparatus were performed. The specific heat and thermal conduction of the apparatus were calibrated with a solid aluminum "dummy cell" of known specific heat. At a given environmental chamber temperature, the heater inside the assembly provided sufficient heat for particular initial internal temperatures. Measurements of temperature after heating provided the necessary calibration data. The specific heat of a particular cell was evaluated by replacing the "dummy cell" with the discharged, shorted cell of known weight. While the initial external (environmental chamber) temperatures were 60-140°C, the internal temperatures

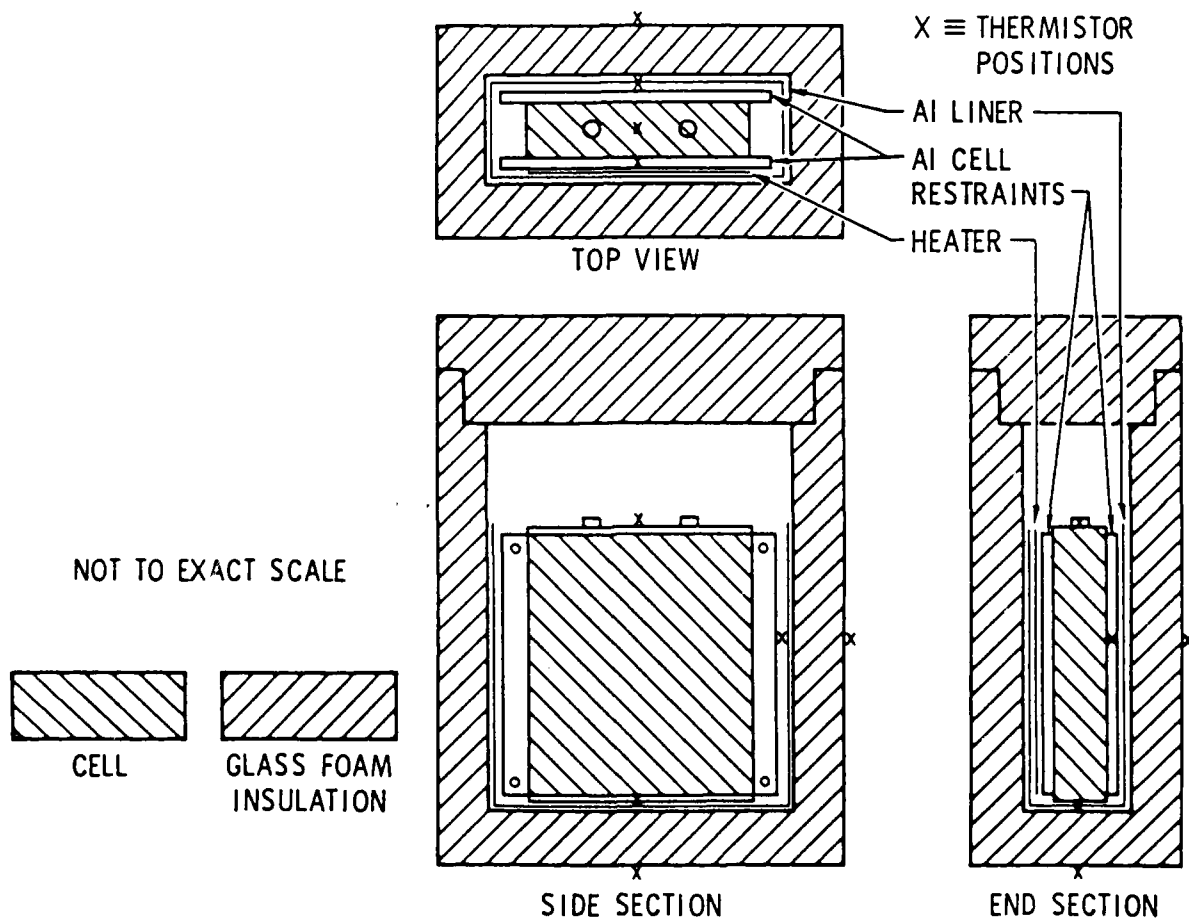


Fig. 1. Thermal Test Assembly

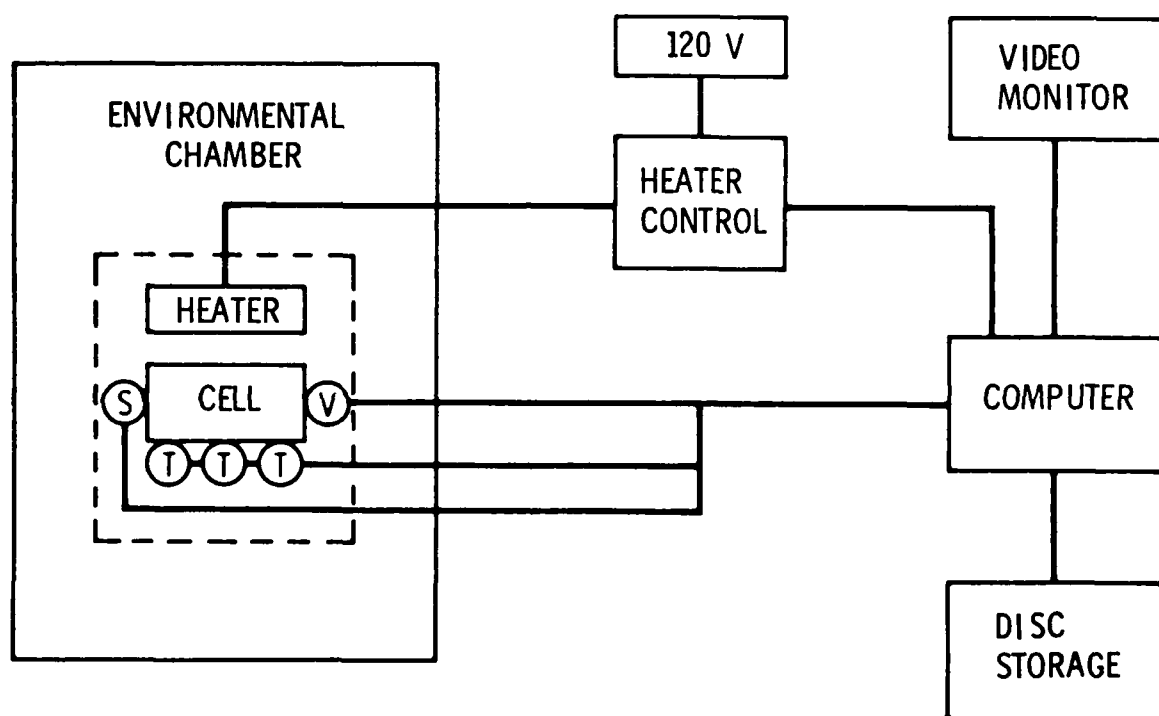


Fig. 2. Block Diagram of Test Apparatus



for the calculation were between 60 and 200°C. The specific heats of other cells were based on these results and on the cell weights.

The thermal processes operating in the experimental test fixture during the calibration runs with a dummy cell of known heat capacity ( $b'$ ) are described by the equation:

$$a \int_{t_1}^{t_2} [T(t) - T'(t)] dt + \frac{c}{2} [T(t_2) - T(t_1) + T'(t_2) - T'(t_1)] = b' [T(t_1) - T(t_2)] \quad (1)$$

where  $a$  is the constant for heat loss through the insulator to the environment,  $c$  is the heat capacity of the insulator,  $T(t)$  = temperature of cell as a function of time, and  $T'(t)$  = the temperature of the chamber as a function of time.

The experiments were performed with fully charged cells at initial internal and external temperatures of 44, 64, 82, 85, and 118°C. The temperatures following the initial heating were monitored for up to 48 hr and provided the data necessary for calculating the self-heat generation of each NiCd cell over the temperature range. The testing procedure was first to heat the test chamber to the preset test temperature, then to heat the cells to approximately the same temperature via timed resistance heaters contained inside the insulators in contact with the cell surface (see Fig. 1), at the rate of  $\sim 1^\circ\text{C}/\text{min}$ . One hour after the environmental chamber reached the setpoint temperature, the cell heaters were fed a predetermined amount of energy, calculated from the cell constant and sufficient to bring the cells and other contents of the insulating containers to the setpoint temperature. Thereafter the chamber temperature was maintained, and both chamber and cell temperatures were monitored. As in the earlier calibration runs, each cell had five thermistors attached to it, and three thermistors were attached to the outside surface of the insulator (Fig. 1). The thermistor readings were monitored at intervals throughout the test, and the data were stored on floppy disks. Values of the cell surface temperatures were averaged prior to the succeeding calculation of self-discharge rates, as were chamber temperatures.

### III. RESULTS OF CALIBRATION

Figure 3 is a computer plot of actual data for selected thermistors from one of the "dummy cell" runs, which was performed in order to determine the specific heat of the apparatus and the heat dissipation rate through the walls of the cell-insulating container at various temperatures and temperature gradients. In this case both the dummy cell and the chamber were brought initially to 60°C, then the cell heaters were disconnected and the cell surface temperatures were monitored for 1 hr. The dummy cell was then heated to successively higher temperatures, and the temperatures after each heating were monitored. The chamber temperature, nominally constant, demonstrated a small upward drift throughout the test, in addition to a significant ripple associated with the cell heating and cooling cycle.

The calculation of the insulator heat capacity,  $c$ , and the heat dissipation rate through the walls of the container,  $a$ , was determined from direct analysis of the energy uptake of the system during periods of active heating and by determining the cooling rates (heaters off), respectively.

The heat capacity ( $b$ ) of the 35 Ah cells that are the subject of this test was determined by calculation from the materials of construction of the cells. The value obtained for a fully discharged cell was then adjusted by calculation to account for the differences in the heat capacity between the charged and discharged active cell materials. A value of  $\Delta H$  (cell) of 0.235 Wh/°C (202 cal/°C) was derived from this calculation, in good agreement with data found in the literature.<sup>1</sup>

The values derived for the various thermal parameters are as follows:

Heat dissipation rate	0.108 kcal/hr°C
Cell heat capacity	0.202 kcal/°C
Cell restraint heat capacity	0.186 kcal/°C
Insulation heat capacity	0.134 kcal/°C

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<sup>1</sup>A. Laursen and P. H. Jacobsen, Analysis and Testing of the Thermal Properties of Space Battery Cells, Contract No. 498/82/NL/JS(SC), European Space Agency (January 1983).

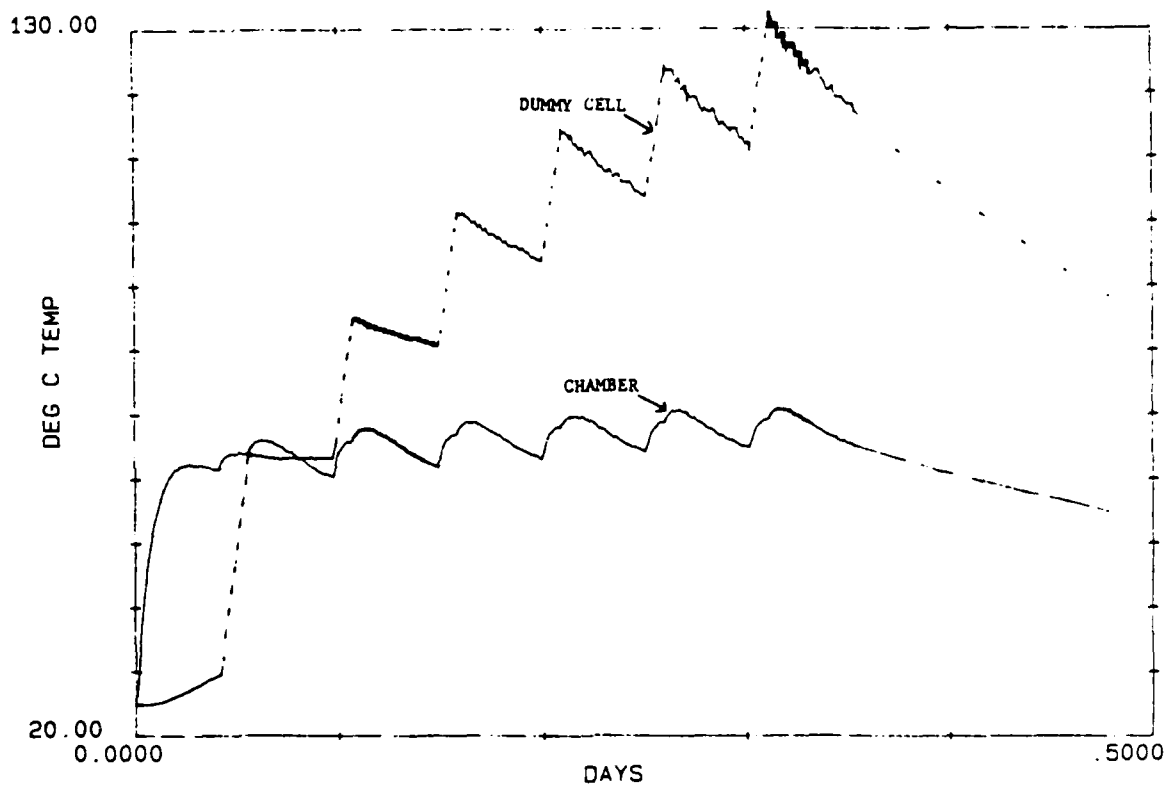


Fig. 3. Temperature vs. Time - Calibration: 60°C Initial Temperature

The limiting uncertainties in the temperature measurements were due to the uncertainties in the analog-to-digital conversion of the thermistor signals. This absolute error was variable with temperature and ranged from 0.1°C or less at ambient to ~ 1°C at 100°C and to several degrees at 200°C. These uncertainties were mitigated in the later cell testing, but were significant in the higher temperature calibration runs; however, the importance of the error was minimal because the temperature differences that are important for purposes of the cell parameter calculations are in general relatively large at the higher test temperatures.

#### IV. NICKEL-CADMIUM CELL TEST RESULTS AND DISCUSSION

In the cell testing, fully charged cells were fastened between restraining plates, fitted with thermistors, etc., and inserted into the insulating housings in the same way that the dummy cells were treated earlier. The same two cells were used for the 64°C tests that were tested at 44°C, after recharge. Otherwise, fresh cells were used in each cell temperature test listed in Table 1.

Example cell and chamber actual temperature data (for simplicity, not all thermistor outputs are shown) appear in Figs. 4 through 8. The thin line between a "safe" condition and one where thermal runaway is a likely result is illustrated in Figs. 6 and 7. At an initial cell temperature of 82°C (Fig. 6), the heat generated by the cell was just able to be dissipated, and the cell temperature rise was slight. At an initial temperature of 85°C (Fig. 7), the heat generated by the cell was greater than could be dissipated through the insulator, and thermal runaway occurred. The cell heating terminated, due to the exhaustion of the energy available in the cell, at a temperature just below where forcible venting could have occurred. In all these plots the chamber temperature was subject to a periodic perturbation, arising from an idiosyncrasy in the test computer program that caused the chamber heaters to actuate at 8 hr intervals.

The calculation of self-discharge rates assumed that all cell capacity and energy losses were converted entirely to heat, and that the heat dissipation rate (D) through the walls of the insulator and the cell thermal capacity derived earlier are constant at all temperatures of the testing. The cell self-discharge rates,  $q$ , at various temperatures were calculated from actual time/temperature data and the calculated slopes of the time/temperature plots with the following equation:

$$q(t) = \left(b + \frac{c}{2}\right) \frac{dT(t)}{dt} + \frac{c}{2} \frac{dT'(t)}{dt} + a [T(t) - T'(t)] \quad (2)$$

Table 1. Cell Temperature Data Summary

Number of Cells Tested	Initial Temperature	Max. Cell Temp. Achieved in Test	Approximate Chamber Temperature <sup>a</sup>
2	~ 44	42	36-38
2 <sup>b</sup>	~ 64	64	58-59
2	~ 82	85	70-72
2	~ 85	166 <sup>c</sup>	72-79
1	~ 118	230	121-129

<sup>a</sup>Periodic overcorrections were omitted (see Figs. 4-8).

<sup>b</sup>Same cells as 44°C test.

<sup>c</sup>Cells were fully discharged.

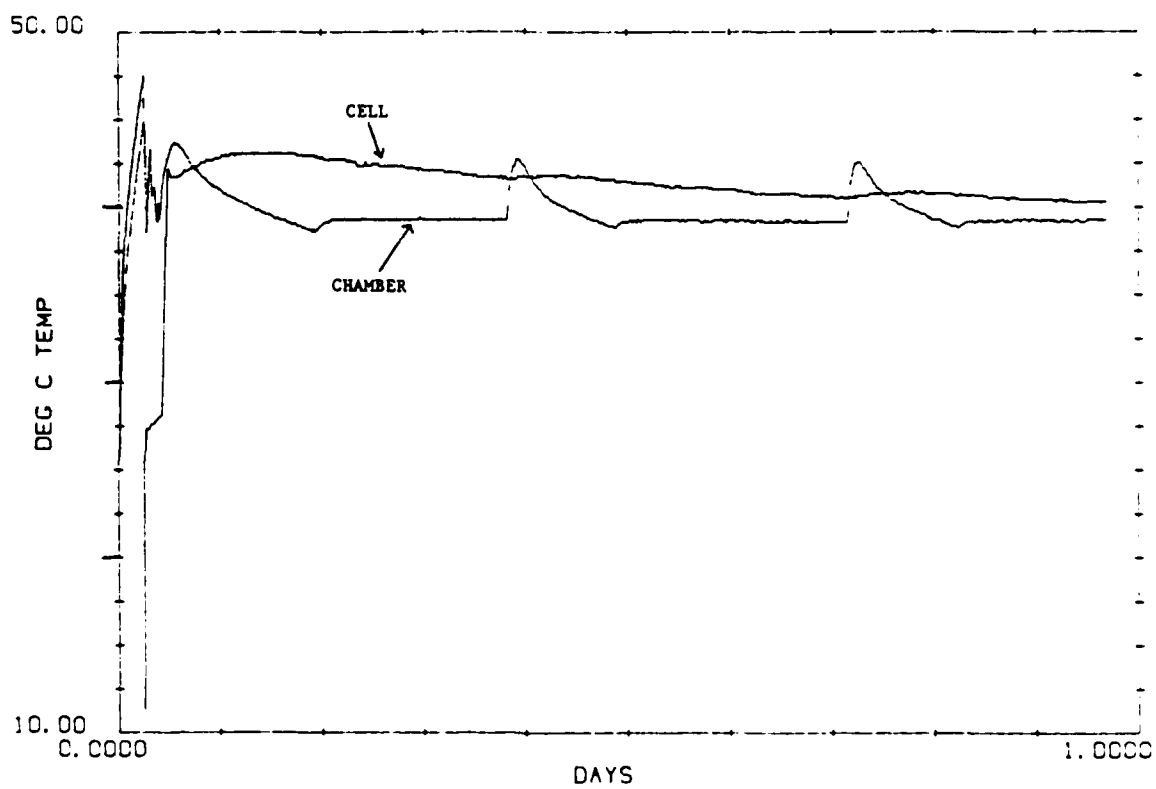


Fig. 4. Temperature vs. Time - Thermal Test: 44°C Initial Temperature

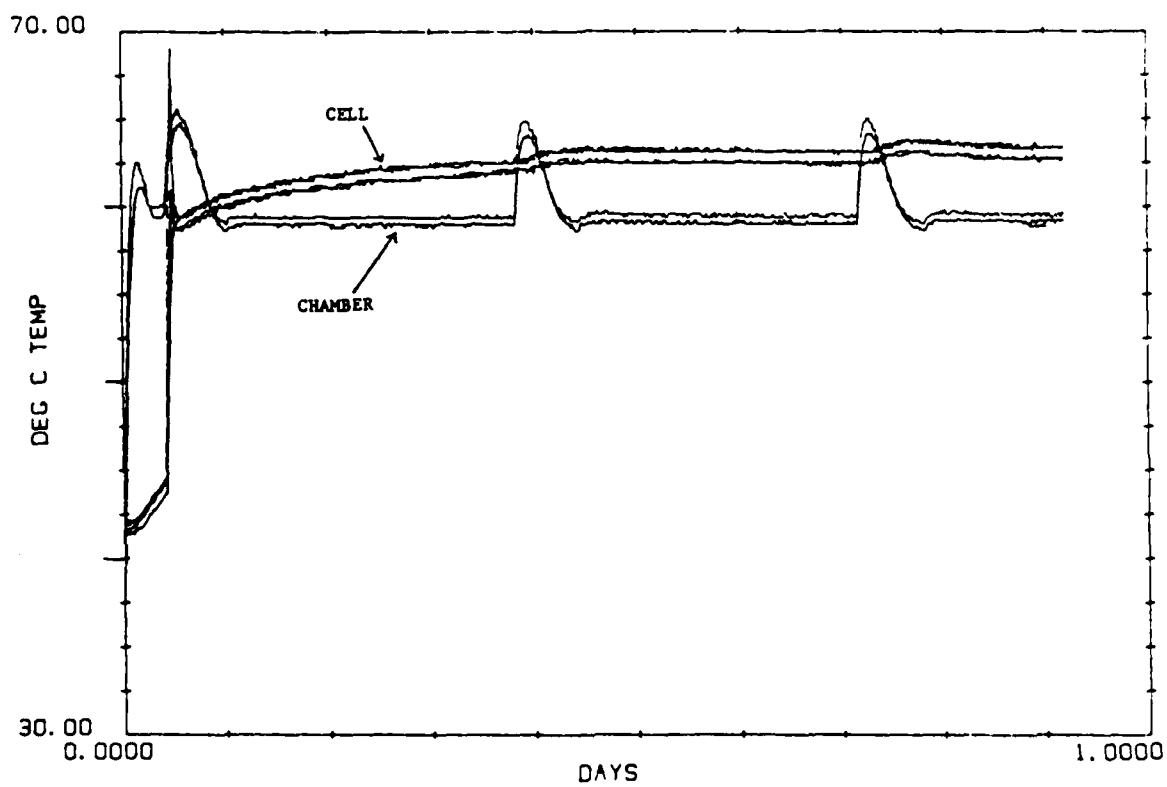


Fig. 5. Temperature vs. Time - Thermal Test: 64°C Initial Temperature



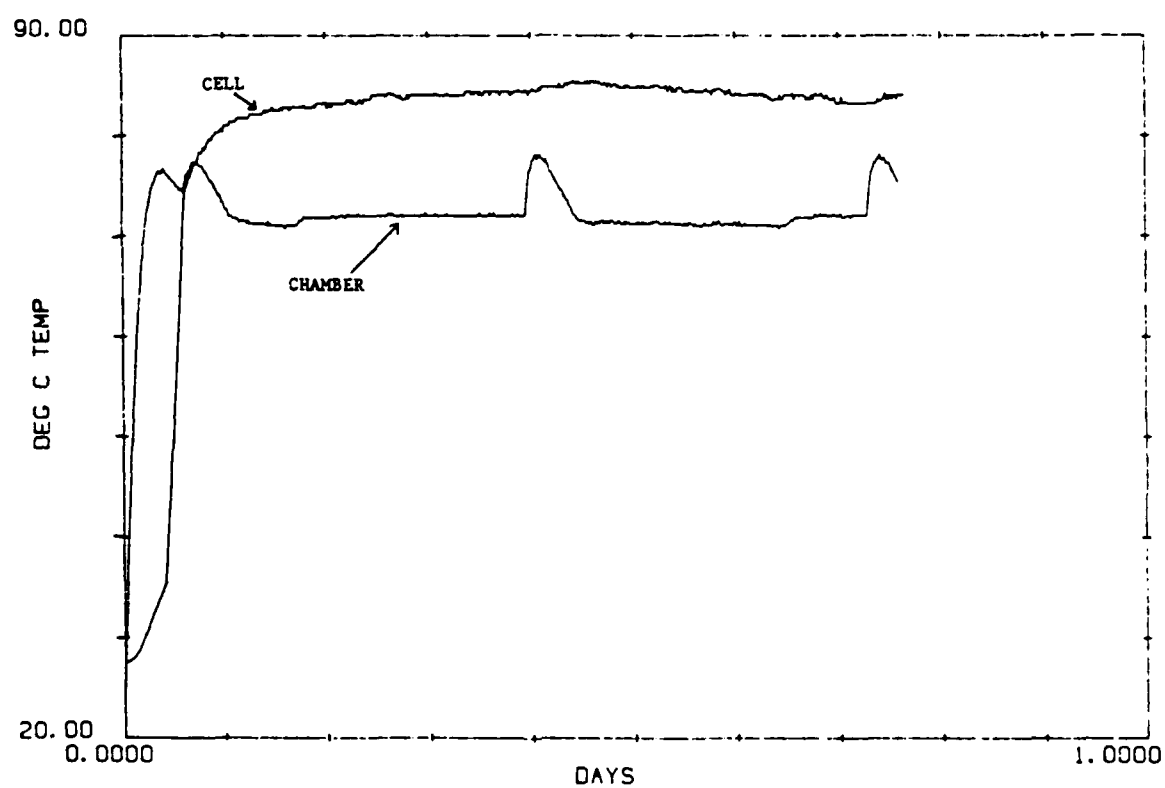


Fig. 6. Temperature vs. Time - Thermal Test: 82°C Initial Temperature

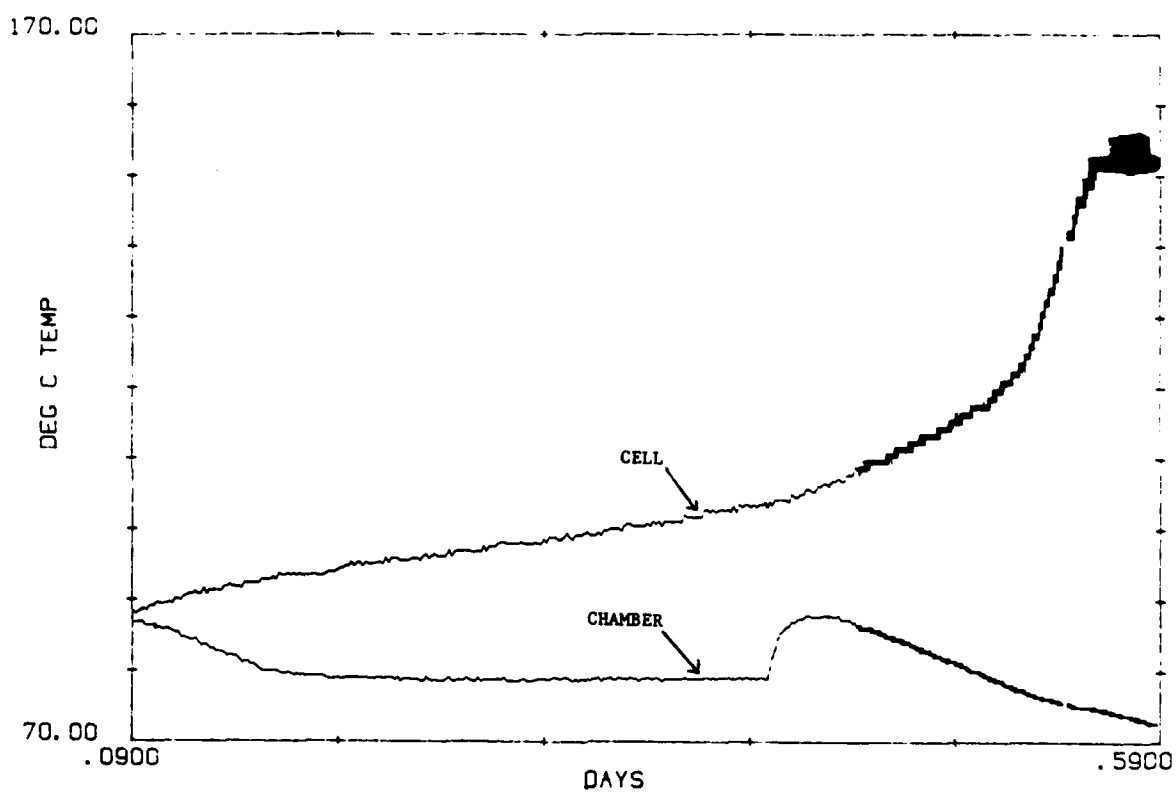


Fig. 7. Temperature vs. Time - Thermal Test: 85°C Initial Temperature

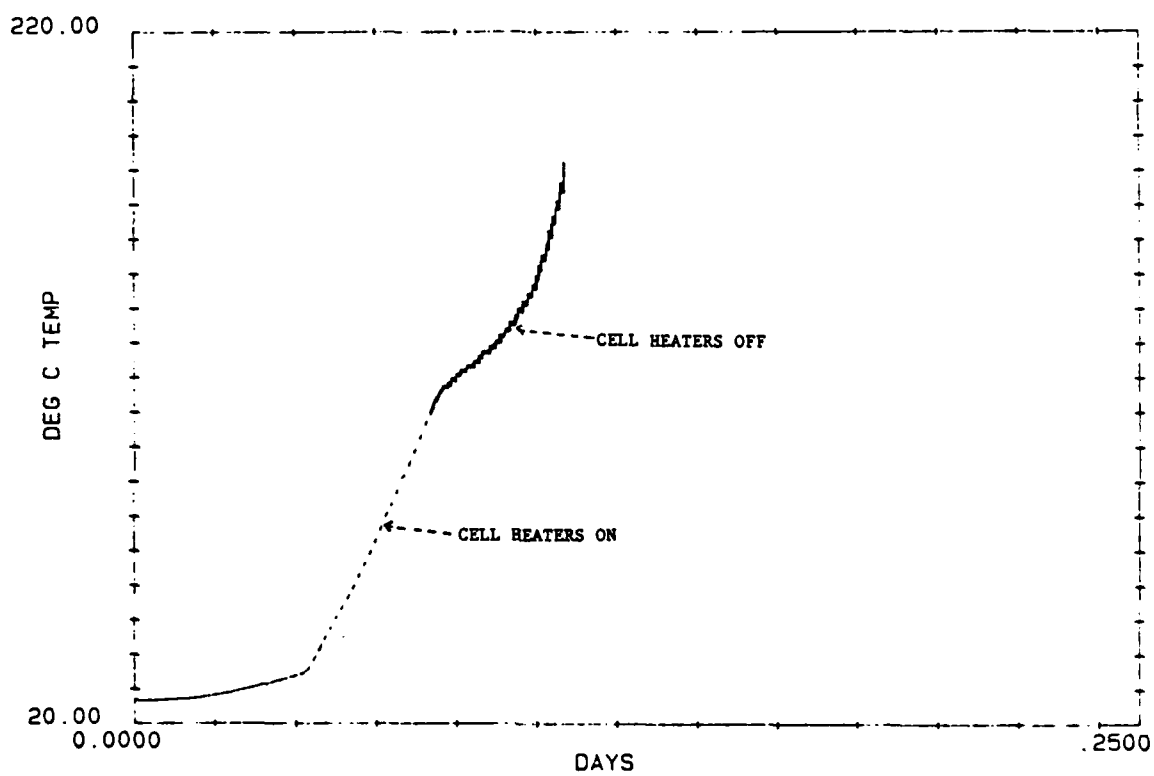


Fig. 8. Temperature vs. Time - Thermal Test: 118°C Initial Temperature

Segments of the time-temperature curves in which the chamber temperature was subject to the periodic perturbation due to an artifact in the software were omitted from these calculations.

The calculated cell self-discharge rates (in watts) at the various test temperatures are plotted (as  $\log q$  vs.  $T^{-1}$ ) in Fig. 9. The data plot is a linear function within the error of measurement, including the point at 40°C (Scott and Rusta<sup>2</sup>). As a practical feature, minimum heat dissipation rates to prevent dangerous thermal conditions from developing as a result of cell self-discharge can be read directly from Fig. 9 for 35 Ah cells weighing 990-1000 g. It should be reasonable to adjust the self-discharge rates proportionately for General Electric NiCd cells of other rated capacities and cell weights. The adjustment should be based on actual capacities; these 35 Ah cells had actual capacities of 36 to 38 Ah. Figure 9 has the capability to be used as a nomogram for calculating dissipation rate requirements for cells open circuited at any temperature. Also, self-discharge rate appears to be relatively independent of state of charge except at the high and low end extremes. For instance, for a cell to withstand 100°C without catastrophic results, at least 2 W of heat dissipation capability would be required. This information can, of course, be extended to cells other than 35 Ah and to batteries in the manner described here. In calculations, it should be remembered that the heat capacities of fully charged and discharged cells are significantly different.

In the 85°C test, the cells were depleted by 158°C and, therefore, did not continue to self-heat. A summation of the total energy dissipated by one of the cells in the 85°C test was made, and the result (50.4 Wh) is in good agreement with that expected (52.3 Wh) for a cell containing 36 Ah initial capacity if discharged throughout at the iso-entropic voltage of 1.454 V.<sup>3</sup> The cells from the 85°C test were recharged in order to determine the extent of damage to performance. Although the cell cases were badly bowed and other

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<sup>2</sup>W. R. Scott and D. W. Rusta, Sealed-Cell Nickel-Cadmium Battery Applications Manual, Reference Publication 1052, NASA, Washington, D.C. (December 1979), p. 101.

<sup>3</sup>A. H. Zimmerman, private communication, The Aerospace Corporation (18 June 1985).

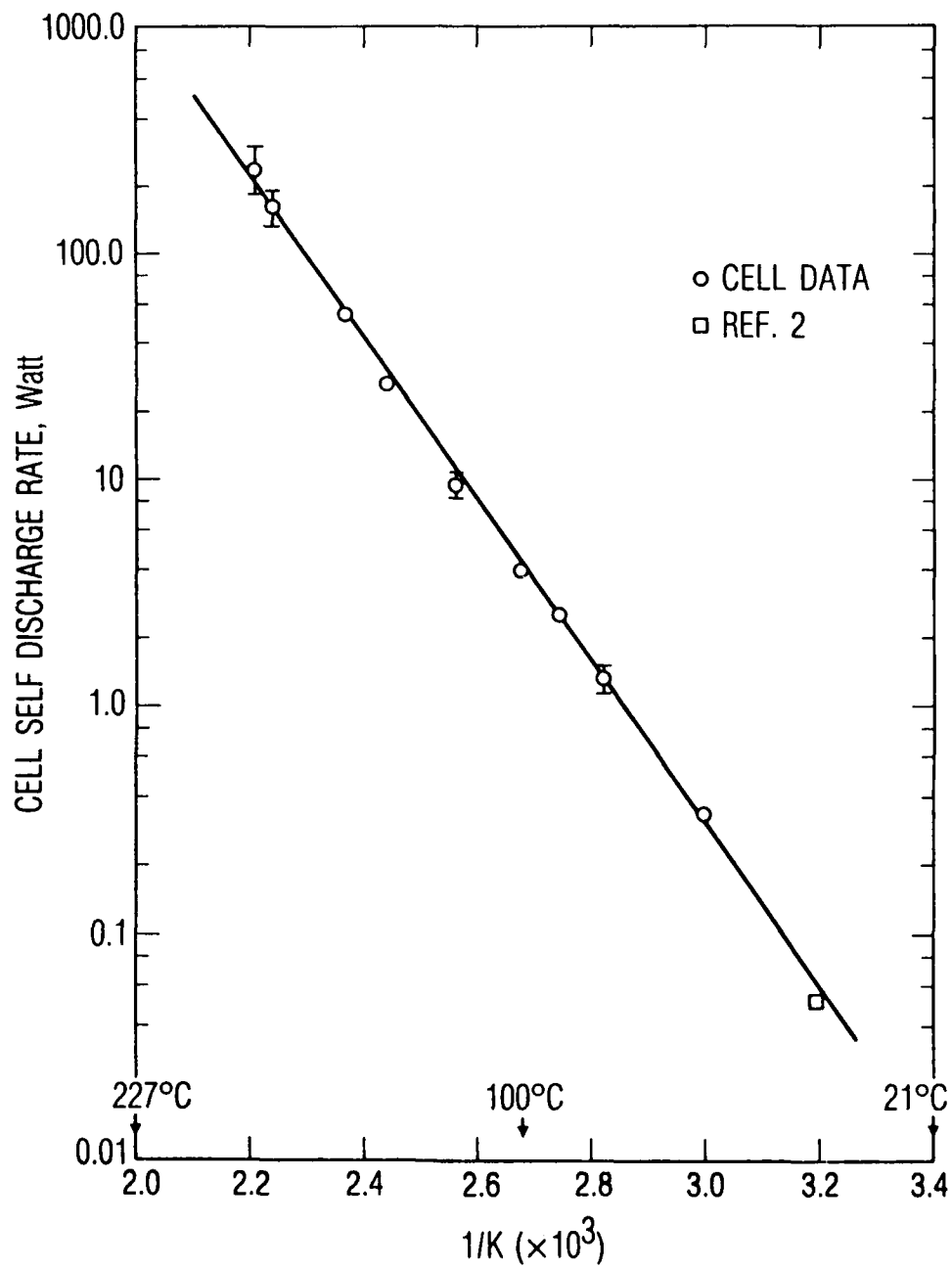


Fig. 9. Log Self-Discharge Rate (W) of 35 Ah NiCd Cells vs.  $1/K (\times 1000)$

signs of external damage were evident (e.g., blackening of the can surface), both cells exhibited 24-26 Ah of capacity (~ 70% of nominal).

We earlier described the cell at 118°C initial temperature as having "ruptured" at cell surface temperatures in excess of 230°C. At the rate of heat generation (>500 W) calculated at a few minutes before the catastrophic event occurred, it is likely that the actual temperature at points within this cell was well in excess of that measured at the cell surface. At these temperatures, it is likely that the separator material fused, allowing the electrode materials to come into intimate contact. At the time of the rupture, the cell retained ~45% of its capacity. Although significant energy must have been rapidly released, we do not have adequate information to judge whether an explosion indeed occurred or merely a forceful venting. However, a decided odor of organic combustion was detected in the surrounding laboratory area after the event. Photographs of the cell chamber and its contents are shown in Fig. 10. The door hinges of the environmental chamber were bent, in spite of a 4 in. diameter hole having been provided for pressure dissipation. As can be seen in the photos, the 1/4 in. aluminum cell restraining plates were bent, while one of four side panels of the cell was blown free. The electrode sinter was covered by black frangible dust, which was all that was left of the active material.

A. CHAMBER INTERIOR



B. REMAINS OF 35 Ah CELL



Fig. 10. Post-Explosion Photographs

## V. CONCLUSIONS

Thermal runaway can occur from elevated temperature self-discharge of charged, open-circuited NiCd cells and batteries. Thermal runaway can be fast enough to rupture cells in batteries and cause physical damage in the surrounding area. Initial battery temperatures  $>80^{\circ}\text{C}$  cannot be allowed in our case. The temperature dependence of the heat generated from the self-discharge reactions has been obtained for the  $40\text{-}200^{\circ}\text{C}$  range. These data may be used to predict necessary heat dissipation rates to the surroundings in order to prevent harmful effects of cell self-discharge at elevated temperatures.



#### LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security projects, specializing in advanced military space systems. Providing research support, the corporation's Laboratory Operations conducts experimental and theoretical investigations that focus on the application of scientific and technical advances to such systems. Vital to the success of these investigations is the technical staff's wide-ranging expertise and its ability to stay current with new developments. This expertise is enhanced by a research program aimed at dealing with the many problems associated with rapidly evolving space systems. Contributing their capabilities to the research effort are these individual laboratories:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photo sensitive materials and detectors, atomic frequency standards, and environmental chemistry.

Computer Science Laboratory: Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence, microelectronics applications, communication protocols, and computer security.

Electronics Research Laboratory: Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, rf systems, electromagnetic propagation phenomena, space communication systems.

Materials Sciences Laboratory: Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; non-destructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

Space Sciences Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.

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